

INSIGHTS INTO THE  $\pi^-p \rightarrow \eta n$  REACTION MECHANISMJ. DURAND<sup>△</sup>, B. JULIA-DIAZ<sup>◦,•</sup>, T.-S. H. LEE<sup>×,•</sup>, B. SAGHAI<sup>△</sup>, and T. SATO<sup>△,•</sup><sup>△</sup>*Institut de Recherche sur les lois Fondamentales de l'Univers, DSM/IRFU, CEA/Saclay,  
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A dynamical coupled-channels formalism is used to investigate the  $\eta$ -meson production mechanism on the proton induced by pions, in the total center-of-mass energy region from threshold up to 2 GeV. We show how and why studying exclusively total cross section data might turn out to be misleading in pinning down the reaction mechanism.

*Keywords:* Multichannel scattering; Pion-baryon interactions

## 1. Introduction

Recent extensive phenomenological studies<sup>1</sup> of the process  $\pi^-p \rightarrow \eta n$  are motivated not only for its interest *per se*, but also by the ongoing development of sophisticated coupled-channels formalisms in order to determine the properties of baryon resonances<sup>2</sup>.

In this contribution we concentrate on the double bump structure observed in the total cross section ( $\sigma_{tot}$ ) of the  $\pi^-p \rightarrow \eta n$  reaction. The first maximum is unambiguously generated by the  $S_{11}(1535)$  resonance, while the origin of the second one is still not well established. Here, we give a very brief account of published findings. All those models include nonresonant terms, and the resonances  $S_{11}(1535)$  and  $S_{11}(1650)$  (hereafter called core terms), but differ in additional resonances and/or the extent of coupled-channels content. With respect to this latter point, they all embody  $\pi N$  and  $\eta N$ , and in some cases  $\pi\pi N$  via  $\pi\Delta$ ,  $\sigma N$ , and  $\rho N$  intermediate-states. Within an early K-matrix approach, Sauermann *et al.*<sup>3</sup>, using the core terms, find no second bump, which appears by adding the  $P_{13}(1720)$ . Gridnev and Kozlenko<sup>4</sup> work based also on the K-matrix, produces a double bump structure in the S-wave only, but the minimum turns out to be roughly two orders of magnitude too low. Penner and Mosel<sup>5</sup> introduce a more elaborated K-matrix coupled-channels with the above mentioned five intermediate-states plus  $\omega N$ ,  $K\Lambda$ , and  $K\Sigma$ . They attribute the second maximum to the  $P_{11}$ -wave and get a good agreement with the data by including also the  $P_{13}$ - and  $D_{13}$ -wave resonances. A direct-channel constituent

quark model<sup>6</sup> finds also  $P_{11}$ -wave crucial with respect to the second bump. Finally, Gasparyan *et al.*<sup>7</sup>, in a more comprehensive version of the Jülich meson-exchange model, obtain a good agreement with the data *via* the core terms plus the  $P_{13}(1720)$ , with small contribution from the  $D_{13}(1520)$ , but their angular distributions for the  $d\sigma/d\Omega$  deviate (significantly) from the data above  $W \approx 1.65$  GeV.

In Sec. 2 we outline our approach and in Sec. 3 our findings are presented, showing how the interplay of various resonances might lead to different conclusions through  $d\sigma/d\Omega$  or  $\sigma_{tot}$ .

## 2. Formalism and model

A dynamical coupled-channels formalism<sup>2</sup>, proven to be successful in studying the  $\pi N \rightarrow \pi N$  reactions<sup>8</sup>, is used to investigate<sup>1</sup> the  $\eta$ -meson production on the proton induced by pions. The coupled-channels equations are derived from standard projection operator techniques. The nonresonant interactions are deduced from a unitary transformation method, applied on a set of phenomenological Lagrangians<sup>2</sup>. This approach includes intermediate  $\pi N$ ,  $\eta N$ ,  $\pi\Delta$ ,  $\sigma N$ , and  $\rho N$  channels and all three and four star resonances with  $M \leq 2$  GeV, namely,  $S_{11}(1535)$ ,  $S_{11}(1650)$ ,  $P_{11}(1440)$ ,  $P_{11}(1710)$ ,  $P_{13}(1720)$ ,  $D_{13}(1520)$ ,  $D_{13}(1700)$ ,  $D_{15}(1675)$ , and  $F_{15}(1680)$ . The model *B* reported in Ref. [1] is used in the present work, and hereafter called the full model. That model is obtained by fitting *exclusively* the  $d\sigma/d\Omega$  data for the reaction  $\pi^- p \rightarrow \eta n$  ( $W \lesssim 2$  GeV), leading to a reduced  $\chi^2 = 1.96$ . Consequently, the  $\sigma_{tot}$  results reported in the next section are predictions from that model.

## 3. Results and discussion

Total cross section as a function of total c.m. energy is depicted in Fig. 1. The full model describes satisfactorily the data. The main feature of the data is two bumps at around 1.560 and 1.710 GeV, with a minimum at roughly 1.660 GeV. To get deeper insights into the structure of the  $\sigma_{tot}$ , we start with results from the background terms and show contributions from the most significant resonances<sup>1</sup> introducing them one after another.

The background terms produce a smoothly varying behavior, the value of which becomes sizable close to the observed minimum. Adding the  $S_{11}(1535)$  to this latter gives the essential features of the  $\sigma_{tot}$ , especially the position and the size of the first peak, but overestimates the data in the range  $1.6 \lesssim W \lesssim 1.7$  GeV. By adding on top of the previous terms the  $S_{11}(1650)$ , the full model's results are almost recovered. Accordingly, the minimum emerges from destructive interference between the two  $S_{11}$ -resonances. Hence, the second maximum appears just because of vanishing contribution from the second  $S_{11}$ -resonance for  $W \gtrsim 1.7$  GeV, its magnitude being hence produced by the first  $S_{11}$ -resonance. Introducing additional resonances, the shape is not altered. Actually, the decrease of the  $\sigma_{tot}$  because of the  $P_{11}(1440)$  is compensated by the  $P_{13}(1720)$ , while the  $D_{13}(1520)$  and  $F_{15}(1680)$  introduce small

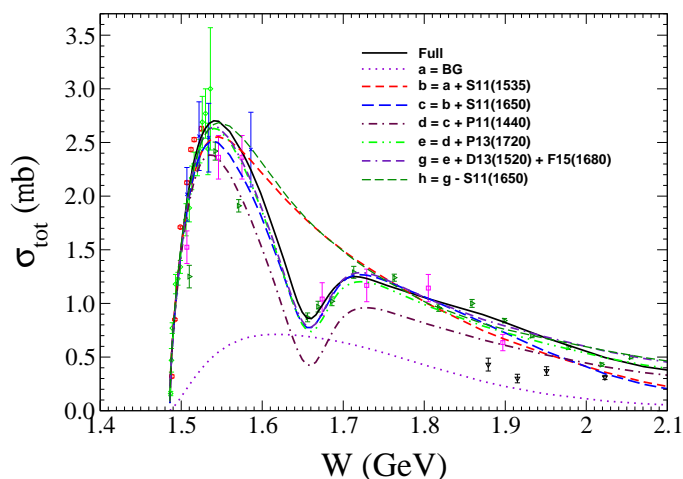


Fig. 1. Total cross section for the process  $\pi^- p \rightarrow \eta n$  as a function of total c.m. energy. Curves (a) to (g) are obtained for background, and then adding one after another resonances  $S_{11}(1535)$ ,  $S_{11}(1650)$ ,  $P_{11}(1440)$ ,  $P_{13}(1720)$ , and  $D_{13}(1520)$  plus  $F_{15}(1680)$ . Curve (h) contains all those resonances except the  $S_{11}(1650)$ . The full model embodies all those terms plus the  $D_{13}(1700)$  and  $D_{15}(1675)$ . Data<sup>9</sup> are from Deinet *et al.* (crosses), Brown *et al.* (right triangles), Crouch *et al.* (down triangles), Debenham *et al.* (up triangles), Morrison (diamonds) and Prakhov *et al.* (empty circles).

contributions. The effects of the  $D_{13}(1700)$  and  $D_{15}(1675)$ , found negligible<sup>1</sup>, are not depicted. Finally, we show the results with all above terms except the  $S_{11}(1650)$ , endorsing the observation that the structure is due to the interference between the two  $S_{11}$ -resonances.

At the present stage and based on the  $\sigma_{tot}$ , one could conclude that the reaction mechanism involves merely background terms and the lowest lying  $S_{11}$ -resonances. To avoid such a misleading conclusion, we move to the  $d\sigma/d\Omega$ . Here we single out three energies corresponding to the positions of the first and the second maximums, as well as to the  $W$ , where the  $\sigma_{tot}$  comes down to its value of the minimum. There are no data at those energies. However, our model has been successfully compared<sup>1</sup> to all the relevant  $d\sigma/d\Omega$  data.

Figure 2 shows our results for the  $d\sigma/d\Omega$  at the above three energies. The background behaves smoothly and decreases with increasing energy. The  $S_{11}(1535)$  brings in the dominant contribution, while the  $S_{11}(1650)$  has a destructive effect, which is very significant at the lowest energy depicted, explaining the minimum found in the  $\sigma_{tot}$ . It is instructive to notice that, contrary to the  $\sigma_{tot}$ , the sum of those three terms (curve c) is far away from the full model and gives a wrong curvature. The  $P_{11}(1440)$  introduces also a destructive contribution at the two lowest energies, and, more importantly, reverses the curvature of the  $d\sigma/d\Omega$ . While the  $P_{13}(1720)$  amplifies the latter behavior, the  $D_{13}(1520)$  has a small effect. Finally, the correct shape is induced by the  $F_{15}(1680)$ . The last curve (h), contains all those

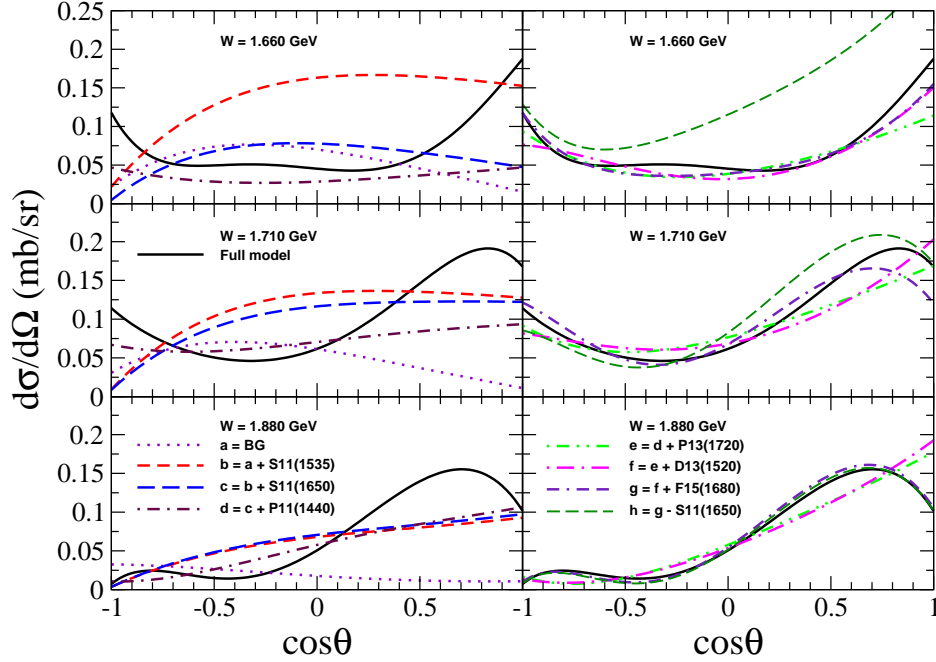


Fig. 2. Differential cross-section angular distribution for the process  $\pi^-p \rightarrow \eta n$  at three energies:  $W=1.660, 1.710, 1.880$  GeV. Curves notations are the same as in Fig. 1.

resonances except the  $S_{11}(1650)$ . The corresponding curve shows very significant deviations from the full model at the lowest energy. That effect is suppressed at the next energy and vanishes at the highest one.

In summary, using a dynamical coupled-channels approach embodying all known three and four star resonances and reproducing satisfactorily differential and total cross section data for the process  $\pi^-p \rightarrow \eta n$ , we have shown that (i) the structure of the  $\sigma_{tot}$  is dictated by the  $S_{11}(1530)$  and  $S_{11}(1650)$  interference, (ii) those  $S$ -wave resonances are by far insufficient to reproduce the differential cross section data.

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